



Responses of urban ecosystem health to precipitation extreme: A case study in Beijing and Tianjin

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ABSTRACT

Our research explores the relationship between precipitation extreme and urban ecosystem health by using emergy analysis based on urban ecosystem health assessment and Difference-in-Difference approach. In the case study area of Beijing and Tianjin, their urban ecosystem are getting healthier with the average growth rate of the key index, urban ecosystem health, are 0.23 and 0.12 respectively, simultaneously the overall index of Beijing is a little higher than that of Tianjin. Meanwhile, urban ecosystem seemingly has nothing to do with precipitation extreme, and the health of its urban sub-ecosystem performs significantly to the precipitation extreme except the sub-ecosystems, resilience, public services and human health. Vigor, one of the urban sub-ecosystems, its ecosystem health negatively associated with precipitation extreme. And urban sub-ecosystem health of vigor will reduce 14.42 if a precipitation extreme happens. The precipitation extreme has a positive effect on organization and emergies. And urban sub-ecosystem health of organization and emergies will increase 44.11, 12.02 respectively if a precipitation extreme happens. In addition, it is apparently nonsignificant to the sub-ecosystems, resilience, public services and human health. Moreover, the extreme precipitation consumes more emergies for the city, it seems beneficial for emergy flow for that precipitation extreme negatively affects emergy/dollar ratio, environmental loading rate and positively affects total emergy. But the extreme precipitation also negatively influences emergy yield ratio. Thus, urban ecosystem health associates with precipitation extreme in a complex way, both positively and negatively. Government measures for recovering urban ecosystem health should emphasize the sub-ecosystem vigor of the city, like constructing more public facilities. And policy makers may pay more attention on environmental loading rate, like advocating improving emergy use efficiency.

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1. Introduction

There is a broad recognition that global climate is changing over history, not only generally referring to global warming, but also extremes, such as rainstorm, which are projected to increase in intensity and magnitude (Kunkel et al., 2013). The 5th assessment report from Intergovernmental Panel on Climate Change (IPCC) has found that global land surface temperature was increased by 0.85 from 1880 to 2012, and it also has indicated that the past three

decades is the hottest period during the last 14 centuries. Meanwhile, mounting studies have indicated that global warming affects precipitation characteristics, containing its amount, frequency, intensity and distribution patterns. Meteorologists have also stated that the water holding capacity of air increased by about 7% with per 1 °C warming, and the rising air moisture can produce more intense precipitation extremes (Trenberth, 2011). Particularly, China is dominated by monsoonal climate and accompanied by a continental arid climate in the northwest and a cold highland climate on the Qinghai-Tibet Plateau in the southwest (Ge et al., 2016). It is frequently affected by a variety of extreme precipitation and drought events due to its strong influence of monsoonal climate. Ma et al. (2015) concluded that the frequencies of dry days, trace days and all precipitation events over China were 56%, 12% and 31% respectively.

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However, as agriculture intensified and urbanization spreads, immeasurable social assets and expensive infrastructure are exposed to climatic disasters. Report from the National Centers for Environmental Information (NCEI) has estimated that U.S. experienced 203 extremes with 5.5 billion-dollar events happening annually during 1980–2016, where overall damages exceeded 1.1 trillion dollar. The records have also denoted that each of the 15 billion dollar damages caused by weather disasters including three rainstorms in 2016 in U.S. (<https://www.ncdc.noaa.gov/billions/>). In China, [Chen and Sun \(2015\)](#) and [Song et al. \(2007\)](#) described that precipitation extremes were also frequently happened during the past 50 years and caused immeasurable damages. National Development and Reform Commission (NDRC) reported in 2013 that extremes gave rise to over 2000 people's death and approximately 0.2 trillion yuan direct damages annually since 1990s. Thus, precipitation extreme is one of the most destructive events for human society and it has attracted more attention due to the large-scale losses. And these trends impose heavy burdens on risk mitigation ([Revi, 2008](#)).

Moreover, ecosystem is vulnerable to climatic disasters, especially precipitation extremes. A high proportion of these vulnerabilities are in urban areas for a number of human's lives killed and public properties devastated in storms and floods ([Olorunfemi and Raheem, 2013](#)). Although the public throws the spotlight on direct monetary losses and deaths, indirect damages such as epidemics, environmental degradations grossly are underemphasized and less assessed. [NDRC \(2013\)](#) has announced that ecosystem, providing goods and services for sustainable development, is declining because of intensive precipitation extremes. But how did precipitation extreme affect ecosystem?

Regarding to climatic disasters, people had little choice but to resistance or move. With increasing climatic disasters like precipitation extremes happened in China, urgent measures are needed to enhance ecosystem health for risk mitigation in the context of climate change. Here, our research is concentrated on urban areas, and what we should do first is to clarify whether precipitation extremes affect urban ecosystem health, and if it do then how it works.

However, what is urban ecosystem health? There seems no unequivocal concept on it. Similar to ecosystem health, [Su et al. \(2010\)](#) summarized that a healthy urban ecosystem possessed three characteristics:

- (i) Urban ecosystem services maintain a productive capacity;
- (ii) System integrity is key component of urban ecosystem health;
- (iii) Assessing urban ecosystem health requires a systems perspective.

Rapport in 1989 stated clearly that a healthy ecosystem was defined as being 'stable and sustainable', maintaining its organization and autonomy over time and its resilience to stress ([Appendix](#)). However, urban ecosystem is a complex system, it is affected by a broad suite of state factors, and its healthy assessment should consider both human wellbeing and the integrity of natural system, incorporating social-economic-ecological factors ([Pickett et al., 2011](#); [Shi and Yang, 2014](#)). [Olorunfemi and Raheem \(2013\)](#) indicated that the complexity of urban ecosystem multiplied risk from climatic disasters. High population density, growing poverty, inequality and inadequate infrastructure in crowded urban is against risk mitigation when precipitation extreme occurs.

Our research has empirically analyzed the relationship between precipitation extreme and urban ecosystem health in Beijing via three steps. Firstly, we have assessed urban ecosystem health based

on a measurable index system composed by 50 key indicators. Meanwhile, these indicators are selected to depict urban ecosystem in terms of six aspects, the vigor, organization, resilience, public services, human health and emerge in Beijing. Secondly, Tianjin, a comparative city is selected to answer whether precipitation extreme affect urban ecosystem health via comparatively analyzing the results of assessment of the two cities. Thirdly, we design a difference in difference (DID) experiment to detect that to what extent precipitation extreme has influenced urban ecosystem health for Beijing and Tianjin.

2. Study area

Our study area is Beijing (39.4°–41.6°N, 115.7°–117.4°E), situated in the north of North China Plain and bounded by Hebei province and Tianjin. Beijing is the capital of China, as well as the economic, political and cultural centre of modern China, with a total area of 16410.54 square kilometers. It is characterized by monsoon variability where an annual average precipitation is approximate 488 mm. In 2012, the mean precipitation was 733.2 mm and reached its peak during the past 50 years. In line with the records from [Weather China \(2012\)](#), the extraordinary rainfall in 2012 gave rise to urban waterlogging and numerable economic damages. Extensive forestry, many tourist attractions, agricultural crops and green belt in Beijing were partially destroyed in this disaster, which had a compound impact on urban ecosystem health.

Tianjin (38°34'–40°15'N, 116°43'–118°04'E) is selected as a comparative city to detect whether precipitation extreme affects urban ecosystem health. It is located at the eastern edge of China and close to the Bohai sea. Tianjin occupies 11916.85 square kilometers and creates 1.65 trillion yuan in 2015. As Tianjin is so close to Beijing, a large part of climatic conditions are similar.

3. Materials and analytic frameworks

An adequate index system is established in this section based on literature review to assess urban ecosystem health of Beijing and Tianjin. Hence urban ecosystem health is taken as a vital dependent variable here in the Difference-in-Difference (DID) model to clarify how precipitation extreme affects urban ecosystem health.

3.1. Emergy-based assessment of urban ecosystem health

3.1.1. Materials and index system

Combining with a broad literature review, indices framework is developed based on the principles of its quantifiable, data availability, regionality, objective and representative. All these indicators are divided into six categories and related references are listed in [Table 1](#). Respectively, vigor is measured the urban ecosystem from the perspective of its activity, metabolism or primary productivity ([Rapport, 1989](#)). The organization sub-ecosystem describes the diversity and number of interactions between system components. Resilience could be assessed in terms of a system's capacity to maintain structure and function in the presence of stress ([Appendix](#)). Human health is measured by a series of indicators represent human's physical and mental health. Emergy flow of the city can be assessed based on emergy analysis, and key emergy indices are introduced into the complex system. Indicators highlighted in [Table 1](#) implies that the higher the value, the worse the sub-ecosystem. In order to alleviate the deviation caused by the data itself, our study got the logarithm of each value at first, and distribute minus sign for those who still opposite to the other indicators.

Table 1
Indicators system for assessing urban ecosystem health for Beijing and Tianjin.

Sub-ecosystem	Indicators	Unit	References
Vigor	growth rate of gross domestic product (x1)	%	Li and Li, 2014
	per capita gross domestic product (x2)	10000 yuan	Su et al., 2009
	disposable personal income (x3)	10000 yuan	Li and Li, 2014
	investment in fixed assets per square kilometer (x4)	yuan	Nakamura, 2003
	proportion of total investment in fixed assets to GDP (x5)	%	Nakamura, 2003; Zeng et al., 2016
	Engel's coefficient (x6)	%	Nakamura, 2003
Organization	fertilizer use per hectare cultivated land (x7)	ton	Zeng et al., 2016
	per capita housing area for urban dweller (x8)	m ²	Su et al., 2009
	unemployment rate of urban population (x9)	%	Nakamura, 2003
	financial dependence (x10)	%	Nakamura, 2003
	growth rate of tertiary industry (x11)	%	Zeng et al., 2016
	ratio of tertiary industry (x12)	%	Zeng et al., 2016
	share of employees of tertiary industry (x13)	%	Nakamura, 2003
	annual precipitation (x13)	cm	Nakamura, 2003
	water area percentage (x14)	%	Nakamura, 2003
	cultivated area percentage (x15)	%	Nakamura, 2003
	unused land percentage (x17)	%	Nakamura, 2003
	built-up area percentage (x18)	%	Zeng et al., 2016
	output of scientific research and technical services (x19)	100 billion yuan	Zhang et al., 2006
	energy intensity by GDP (x21)	ton standard coal	Zhang et al., 2006
	population density (x22)	person/km ²	Zeng et al., 2016
	life garbage treatment rate (x23)	%	Shi and Yang, 2014
	sewage treatment rate (x24)	%	Shi and Yang, 2014; Li and Li, 2014
	daily mean inhalable particles (x25)	mg/m ³	Zeng et al., 2016
	daily mean nitrogen dioxide (x26)	mg/m ³	Zeng et al., 2016; Zhang et al., 2006
Public service	number of buses per square kilometer (x27)	-	Li and Li, 2014
	per capita freight volume (x28)	ton	Zeng et al., 2016
	per capita passengers volume (x29)	person	Zeng et al., 2016
	per capita urban road (x30)	person/km ²	Nakamura, 2003
	numbers of phones per thousand persons (x31)	-	Nakamura, 2003
	mean noise on main road (x32)	db	Zhang et al., 2006
	mean noise of the city (x33)	db	Zhang et al., 2006
	number of beds in hospital per thousand population (x34)	-	Nakamura, 2003
	road density (x35)	km/km ²	Li and Li, 2014
	per capita green land (x36)	m ² /person	Nakamura, 2003
Human health	urban green coverage (x37)	%	Zeng et al., 2016
	per capita gas consumption (x38)	m ³	Zeng et al., 2016
	per capita liquefied petroleum gas consumption (x39)	kg	Zeng et al., 2016
	per capita electricity consumption (x40)	kwh	Zeng et al., 2016
	per capita water consumption (x41)	m ³ /person	Zhang et al., 2006
	infant mortality rate (x42)	%	Nakamura, 2003
	growth rate for permanent resident population (x43)	%	Nakamura, 2003
	number of graduates in colleges and universities (x44)	10000 persons	Nakamura, 2003
	average schooling years (x45)	year	Nakamura, 2003
	total energy (x46)	Sej	Su et al., 2009
Emergies	emdollar ratio (x47)	Sej/100 billion yuan	Su et al., 2009
	per capita emery welfare (x48)	Sej/person	Su et al., 2009
	environmental loading rate (x49)	-	Su et al., 2009
	emery yield ratio (x50)	-	Su et al., 2009

All the indicators in Table 1 can be directly obtained and computed based on the data collected from Statistic Yearbook of Beijing and Tianjin during 2001–2016 (Statistic Yearbook 2016 lists

the data of 2015). Raw data for calculating indicators listed in Table 2 can also be obtained from Statistic Yearbook. According to the results of Table 2, indicators in the sub-ecosystem of emery

Table 2
Emery table of Beijing and Tianjin.

Item	unit	Solar transformity (Sej/Unit)	Item	unit	Solar transformity (Sej/Unit)
Renewable sources (R)			Non-renewable resources (N)		
Sunlight	J	1	Soil losses	t	1.71E+03
Wind	J	2.45E+03	Electricity	J	1.60E+05
Rain, chemical	J	3.05E+04	Steels	g	1.80E+09
Rain, geopotential	J	4.70E+04	Cement	g	3.30E+10
Earth cycle	J	5.80E+04	Energy	J	4.00E+04
Agricultural production	g	2.43E+11	Fertilizer	t	8.28E+06
Livestock production	g	1.49E+11	Exports (EX)		
Fisheries production	g	1.80E+10	Goods	\$	6.34E+12
Imports (IM)			Services	\$	Services
Goods	\$	9.37E+12	Waste produced (W)		
Services	\$	9.37E+12	Solid wastes	kg	1.80E+06
Tourism	\$	1.66E+12	Sewage	kg	6.66E+05

Table 3
Emergies indices for Beijing and Tianjin.

Indicators	Equation
total energy	$R + N + IM$
emdollar ratio	U/GDP
per capita energy welfare	$U/population$
environmental loading rate	$(N + IM)/R$
energy yield ratio	$(R + N + IM)/IM$

can be calculated based on the equation in Table 3.

Note: All the definitions of the indicators in Table 3 are listed in Appendix.

3.1.2. Evaluation of urban ecosystem health

Basically, urban ecosystem health assessment can be achieved within four steps, namely standardization of raw data, weight determination, score of the whole urban ecosystem or each sub-ecosystem, and urban ecosystem health assessment (Zeng et al., 2016). Firstly, disturbance of dimension is removed by the mean of standardization.

$$Y_{ij} = \frac{y_{ij} - y_{jmin}}{y_{jmax} - y_{jmin}}, \quad (i = 2000, 2001, \dots, 2015; j = 1, 2, \dots, 50) \quad (1)$$

Where i is the year of observations, and j is the order number of indicators listed in Table 1. Y_{ij} is the standardized value of each indicator, y_{ij} is the raw data of 50 indicators during 2000–2015, y_{jmin} refers to the minimum value of an indicator, and y_{jmax} presents the maximum value of an indicator.

Secondly, weight of each indicator is determined by mean square deviation. The mean square deviation of Y_{ij} can be expressed as follow.

$$\sigma(Y_j) = \sqrt{\sum_{i=2000}^{2015} [Y_{ij} - E(Y_j)]^2}, \quad E(Y_j) = \frac{1}{16} \sum_{i=2000}^{2015} Y_{ij} \quad (2)$$

Then, equation (3) expresses the weight of all the indicators of the whole urban ecosystem (ω_{1j}), the weight of the indicators of each sub-ecosystem (ω_{2j}) can be achieved by equation (4). Taken

the sub-ecosystem human health as example, the weight of the indicators (x42, x43, x44, x45) of human health (ω_{2hhj}) can be computed by equation (5).

$$\omega_{1j} = \frac{\sigma(Y_j)}{\sum_{j=1}^{50} \sigma(Y_j)} \quad (3)$$

$$\omega_{2j} = \frac{\sigma(Y_j)}{\sum_{j=n}^m \sigma(Y_j)} \quad (4)$$

$$\omega_{2hhj} = \frac{\sigma(Y_j)}{\sum_{j=42}^{45} \sigma(Y_j)} \quad (5)$$

Where $\sigma(Y_j)$ refers to the mean square deviation of Y_{ij} , $E(Y_j)$ is mean value of standardization of Y_{ij} . n and m are the order number of the indicator of each sub-ecosystem.

Thirdly, the score of each indicator of the whole urban ecosystem and six sub-ecosystems can be obtained as follow.

$$S_{1ij} = \omega_{1j} \times Y_{ij} \quad (6)$$

$$S_{2ij} = \omega_{2j} \times Y_{ij} \quad (7)$$

Fourthly, the whole urban ecosystem health and the health of each sub-ecosystem are computed by weighted mean (Table 4).

$$UEH_{1j} = \sum_{j=1}^{50} S_{1j} \quad (8)$$

$$UEH_{2j} = \sum_{j=n}^m S_{2j} \quad (9)$$

3.2. Difference-in-difference model (add references in this part)

A Difference-in-Difference (DiD) approach is used in our study to estimate causal effects between precipitation extreme and urban ecosystem health. This method is prevailing on clarifying the effects of policy interventions in empirical research (Athey and Imbens,

Table 4
Weight of indicators of Beijing and Tianjin.

Indicators	Beijing		Tianjin		Indicators	Beijing		Tianjin		Indicators	Beijing		Tianjin	
	ω_{1j}	ω_{2j}	ω_{1j}	ω_{2j}		ω_{1j}	ω_{2j}	ω_{1j}	ω_{2j}		ω_{1j}	ω_{2j}	ω_{1j}	ω_{2j}
x1	0.020	0.17	0.019	0.15	x18	0.021	0.066	0.020	0.063	x35	0.022	0.074	0.022	0.074
x2	0.020	0.17	0.023	0.18	x19	0.015	0.049	0.015	0.047	x36	0.022	0.074	0.025	0.084
x3	0.020	0.17	0.022	0.17	x20	0.021	0.066	0.020	0.064	x37	0.017	0.058	0.018	0.062
x4	0.021	0.18	0.022	0.17	x21	0.018	0.056	0.023	0.074	x38	0.021	0.070	0.017	0.056
x5	0.022	0.19	0.023	0.19	x22	0.023	0.074	0.023	0.074	x39	0.020	0.066	0.016	0.052
x6	0.014	0.12	0.017	0.13	x23	0.016	0.19	0.021	0.26	x40	0.021	0.069	0.022	0.073
x7	0.021	0.068	0.021	0.066	x24	0.022	0.27	0.023	0.28	x41	0.021	0.069	0.018	0.058
x8	0.022	0.069	0.019	0.061	x25	0.022	0.27	0.018	0.22	x42	0.022	0.26	0.020	0.25
x9	0.016	0.050	0.013	0.043	x26	0.022	0.27	0.019	0.24	x43	0.023	0.28	0.022	0.27
x10	0.021	0.067	0.022	0.069	x27	0.020	0.067	0.018	0.059	x44	0.017	0.20	0.021	0.26
x11	0.021	0.067	0.020	0.065	x28	0.024	0.081	0.026	0.087	x45	0.021	0.25	0.017	0.22
x12	0.019	0.061	0.018	0.055	x29	0.025	0.083	0.017	0.057	x46	0.023	0.21	0.021	0.21
x13	0.022	0.069	0.017	0.055	x30	0.016	0.054	0.023	0.075	x47	0.017	0.16	0.020	0.20
x14	0.019	0.060	0.019	0.061	x31	0.020	0.067	0.021	0.071	x48	0.024	0.22	0.021	0.21
x15	0.020	0.064	0.019	0.062	x32	0.015	0.050	0.019	0.064	x49	0.022	0.20	0.020	0.20
x16	0.016	0.050	0.023	0.074	x33	0.019	0.064	0.019	0.065	x50	0.023	0.21	0.020	0.20
x17	0.020	0.064	0.020	0.065	x34	0.016	0.053	0.019	0.063					

2006). The prerequisite to conduct this method is that policy changes haven't affected every sample or the whole study area at the same time, so that we can separate treated group and control group. DiD is also used in the field of physical sciences, such as experimental science. However, the research designs should satisfy three basic hypotheses, first, the intervention only affect the treatment group and has nothing to do with the control group. Second, macro environment for treatment group and control group is the same during research period. Third, critical characters don't vary over time. Here, "time" often acts as a distinguished variable to separate groups. Besides the group which have already received the treatment (post-treatment treated group), the other three are respectively the group in the period that hasn't received treatment (pre-treatment treated group), the nontreated group before intervention took place (pre-treatment control group), and nontreated group in the current period (post-treatment control group) (Dimick and Ryan, 2014). Thus the strategy can capture whether the two treated and the two nontreated groups are subject to the same trends.

Our study starts with a simple set-up that whether precipitation extreme happened or not in Beijing and Tianjin from 2000 to 2015 to show the effects of precipitation extreme on urban ecosystem health. The treatment (precipitation extreme), denoted by D , is binary, i.e. $d \in \{0, 1\}$, and there are only measurements in two time period, T , $t \in \{0, 1\}$. Period zero ($T_{pre} = 0$) relates to the time before the treatment and period one ($T_{post} = 1$) relates to the time after precipitation extreme took place in treated group (Beijing). Assuming that the treatment happens between the two periods means that every member of the population is untreated in the pre-treatment period. We propose to discover the mean effect of switching D from zero (D^c) to one (D^t) on urban ecosystem health, and also six sub-ecosystems of vigor, organization, resilience, public services, human health and emergies. In addition, our research doesn't incorporate extra control variables into the model, due to that the occurrence of precipitation extreme largely results from unobservable elements. While regarding to the control group (Tianjin), D^c is always equalled to zero because precipitation extreme haven't taken place in Tianjin yet (Table 5). Thus an interaction term ($D \times T$) refers to the treatment states after intervention (Table 6).

Thus the effects of precipitation extreme on urban ecosystem health during 2000–2015 for Beijing and Tianjin can be extracted as shown in Table 6.

$$Y_{it} = \beta_0 + \beta_1 T_{it} + \beta_2 D_{it} + \beta_3 (T_{it} \times D_{it}) + \varepsilon_{it} \quad (9)$$

Table 5
Key dummy variables.

Treated	$D^c = 0$	$D^t = 1$
$T_{pre} = 0$	0	0
$T_{post} = 1$	0	1

Table 6
Theory framework of Difference-in-Difference model.

Treated	Before precipitation event	After precipitation event	Difference
Beijing	$\beta_0 + \beta_2$	$\beta_0 + \beta_1 + \beta_2 + \beta_3$	$\Delta Y_t = \beta_1 + \beta_3$
Tianjin	β_0	$\beta_0 + \beta_1$	$\Delta Y_c = \beta_1$
Difference	—	—	$\Delta \Delta Y_c = \beta_3$

4. Results

4.1. Report of urban ecosystem health in Beijing and Tianjin

As the assessment result and Fig. 1 shown, although urban ecosystem health drops slightly in some year in Beijing and Tianjin, the overall trend of this index is growing over time. Comparatively, mean value of urban ecosystem health in Beijing is 0.37, which is a little healthier than that of Tianjin, whose mean value is 0.33. Similarly, average growth rate of urban ecosystem health is 0.23 in Beijing and it appears to be 0.12 in Tianjin. Thus how does it happen? And which sub-ecosystem does present a different tendency to the index of urban ecosystem health (Fig. 2)?

Calculation of each sub-ecosystem shows that the tendencies of Vigor, Organization, Resilience and Public services are basically same to that of the urban ecosystem health. However, assessment of Human health and Emergies demonstrates different that the mean values of the rest two sub-ecosystems in Beijing are all less than those of in Tianjin, and their average growth rate performs in the same way (Fig. 3).

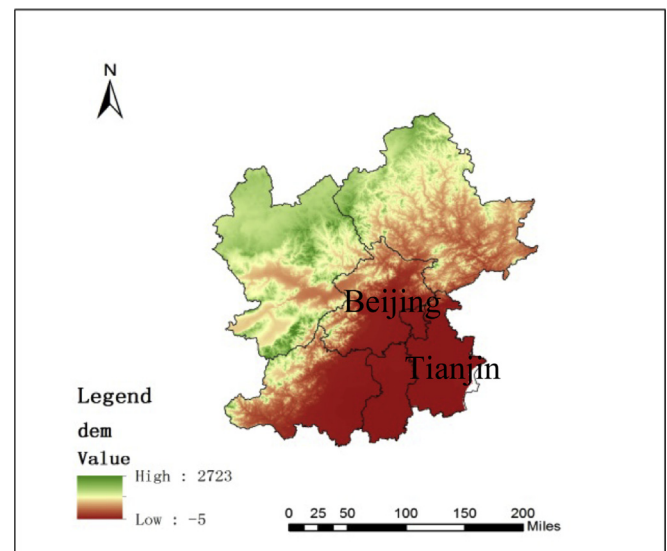


Fig. 1. Geographic map of Beijing and its surrounding cities.

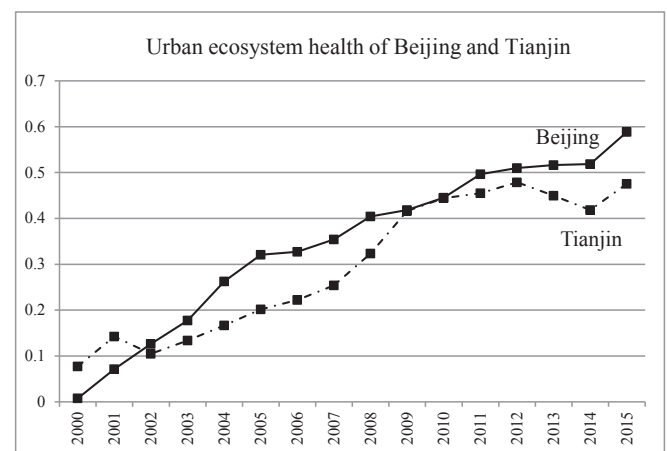


Fig. 2. Urban ecosystem health in Beijing and Tianjin during 2000–2015.

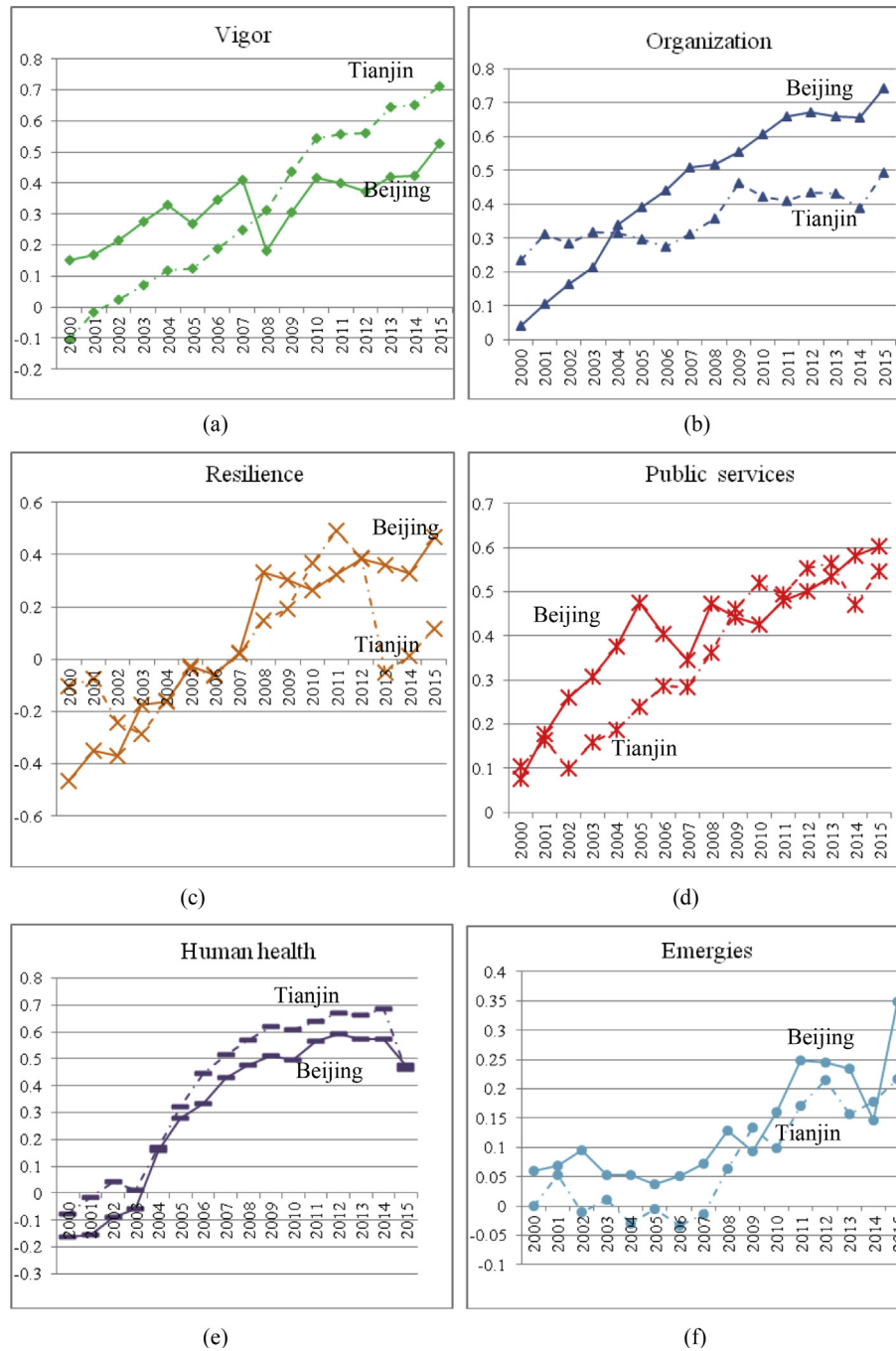


Fig. 3. Urban sub-ecosystem health in Beijing and Tianjin during 2000–2015.

4.2. Impact of precipitation extreme on urban ecosystem health

Impact of precipitation extreme on urban ecosystem health is estimated by the DiD approach. And the results of model in Table 7 implies that precipitation extreme doesn't affect urban ecosystem health due to the nonsignificant of the interaction term. However, the six sub-ecosystems which is decomposed from urban ecosystem, performed different in the models. The results of vigor, organization and emergies show that these three sub-ecosystems are significantly related to precipitation extreme. While the remaining three sub-ecosystems, resilience, public

services and human health have nothing to do with climatic event seemingly.

Respectively, the sub-ecosystems of vigor, organization and emergies are susceptible to precipitation extreme, but only organization sub-ecosystem becomes stronger and the other two are declining after this climatic event. Then in the organization sub-ecosystem, the value of indicators, per capita housing area for urban dweller (x8), the ratio of fiscal revenue to GDP (x10), growth rate of secondary industry (x19) and output of scientific research and technical services (x20) are all still in a growing trend, although the precipitation extreme happens. And all these indicators are

Table 7

Results from Difference-in-Difference approach analyzing the impact of precipitation extreme on urban ecosystem health and urban sub-ecosystem health.

Beijing vs. Tianjin (<i>D</i>)	Pre-precipitation extreme vs. Post-precipitation extreme (<i>T</i>)	Interaction term (<i>D</i> × <i>T</i>)	Constant
Dependent variable: Urban ecosystem health in Beijing and Tianjin from 2000 to 2015 14.99(2.94)***	25.99(3.60)***	13.25(1.30)	53.62(14.86)***
Dependent variable: Vigor in Beijing and Tianjin from 2000 to 2015 −8.27(−2.52)***	28.88(6.22)***	−14.12(−2.15)**	30.39(13.10)***
Dependent variable: Organization in Beijing and Tianjin from 2000 to 2015 33.29 (3.31)***	50.90 (3.58)***	44.11 (2.19)**	105.61 (14.85)***
Dependent variable: Resilience in Beijing and Tianjin from 2000 to 2015 −7.63(−3.80)***	7.68(2.70)***	0.0020(0.00)	42.39(29.85)***
Dependent variable: Public services in Beijing and Tianjin from 2000 to 2015 17.12(3.25)***	20.44(2.74)**	0.35(0.03)	45.58(12.24)***
Dependent variable: Human health in Beijing and Tianjin from 2000 to 2015 1.25(2.16)**	1.99(2.42)**	0.14(0.12)	3.50(8.51)***
Dependent variable: Emergies in Beijing and Tianjin from 2000 to 2015 12.54(8.85)***	−4.96(−2.47)***	12.02(4.24)***	−6.67(−6.65)***

Note: **p* < .1; ***p* < .05; ****p* < .01.

mainly determined by anthropogenic factors, although precipitation disaster give rise to numerable damages, post-disaster reconstruction helps economic recovery. Thus the urban sub-ecosystem health of organization is significantly positive to the precipitation extreme.

4.3. Changes of urban sub-ecosystem health

4.3.1. Impact of precipitation extreme on human health

Moreover, comparing the status of urban sub-ecosystem health of 2015 in Beijing with that of 2010 in the radar map (a), urban sub-ecosystems except human health and emergies are getting healthier. Combining with Table 8, average schooling years (x45) presented significantly negative to the climatic event. As shown in Fig. 4, it is implied that the ratio of primary students is increasing during 2000–2015 both in Beijing and Tianjin. In addition, the climatic disaster broke or even destroyed hundreds of primary schools and high school, and the government gave a great financial assistance to school construction for better education. These two facts are the main reason why the interaction term is negative to the average schooling years. Oppositely, growth rate for permanent resident population (x43) is positive to precipitation extreme. However, the relationship between precipitation extreme and x43 is equivocal, due to the loosening of one-child policy in 2013. Thus, it is certain that the great support from government after natural disaster benefited the

enrollment rate because of the increasing amount of schools (Figs. 5 and 6).

4.3.2. Impact of precipitation extreme on emergy flow

As shown in Table 9, emergy/dollar ratio, environmental loading rate and emergy yield ratio are significant negative, but total emergy presents positive to the occurrence of precipitation extreme. Firstly, as damages generated by the precipitation extreme consumes more emergies for the city, total emergy becomes higher after precipitation extreme. Secondly, emergy/dollar ratio calculated by the total emergy use of a city divided by the urban GDP, is a measure of virtual value and reflects the emergy use efficiency. The higher the value, the lower the efficiency. Thus, emergy use efficiency takes advantages from precipitation extreme because of the increasing trend of total emergy. Thirdly, environmental loading rate can be used to value the environmental pressure from economic system. The higher the value, the greater the pressure. Thus, environment pressure alleviated after precipitation extreme. Fourthly, emergy yield ratio is used to measure the economic contribution of emergy yield, then the climatic event has a negative impact on emergy yield ratio.

5. Conclusion and discussion

Through computing emergy based urban ecosystem health of Beijing and Tianjin, this paper discusses how the precipitation

Table 8

Results from Difference-in-Difference approach analyzing the impact of precipitation extreme on urban sub-ecosystem health of human health.

Beijing vs. Tianjin (<i>D</i>)	Pre-precipitation extreme vs. Post-precipitation extreme (<i>T</i>)	Interaction term (<i>D</i> × <i>T</i>)	Constant
Dependent variable: x42 in Beijing and Tianjin from 2000 to 2015 −1.85(−4.42)***	−1.55(−2.61)***	−0.44(−0.52)	6.32(21.33)***
Dependent variable: x43 in Beijing and Tianjin from 2000 to 2015 0.078(0.18)	−0.025(−0.04)	2.36(2.72)***	1.84(6.01)***
Dependent variable: x44 in Beijing and Tianjin from 2000 to 2015 4.44(3.28)***	5.42(2.84)***	−1.66(−0.61)	6.82 (7.13)***
Dependent variable: x45 in Beijing and Tianjin from 2000 to 2015 0.52(3.21)***	0.48 (2.09)**	−0.71 (−2.19)**	10.74 (93.01)***

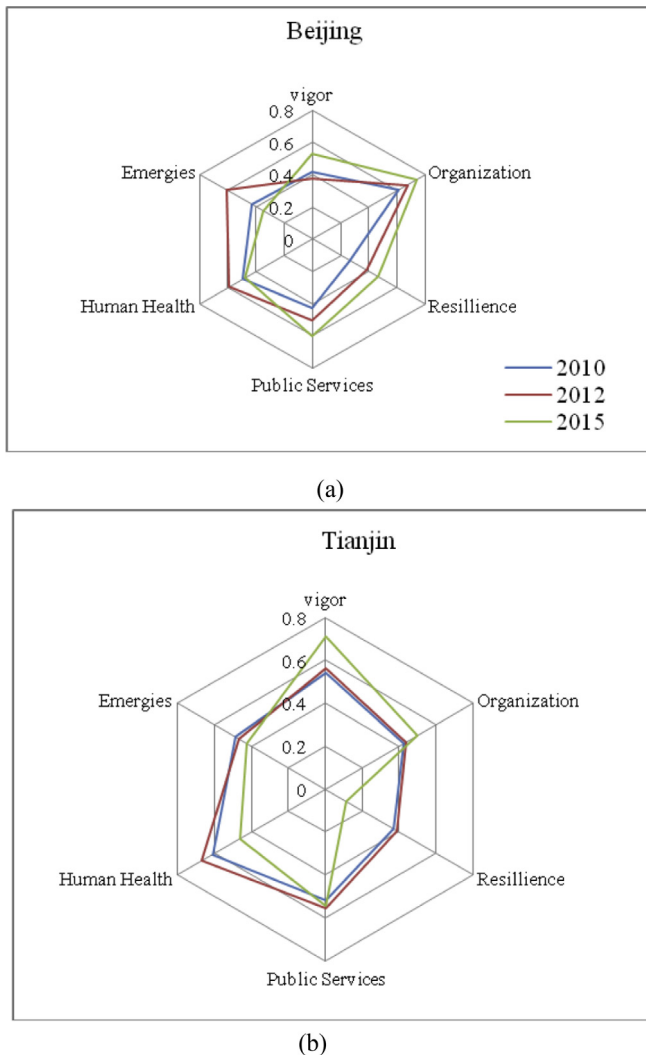


Fig. 4. Radar maps of the urban sub-ecosystem health for Beijing and Tianjin in the year of 2010, 2012 and 2015.

extreme happened in 2012 in Beijing affects urban ecosystem health by using DiD approach. The calculation results show that average urban ecosystem health is 0.37 and 0.33 and its growth rate is 0.23 and 0.12 in Beijing and Tianjin respectively. Based on the analysis above, urban ecosystem health seemingly has nothing to do with precipitation extreme, but it negatively affects urban sub-ecosystem health of vigor and positively affects organization and emergies. Meanwhile, precipitation extreme is apparently nonsignificant related to the sub-ecosystem of human health, but it is negative to human's mental health. As to the energy flow, precipitation extreme presents beneficial to energy flow due to damages caused by the extreme exhausting more non-renewable resources, but it injures energy yield ratio. Thus there is an association between precipitation extreme and urban ecosystem health, and their interactions are intricate. The impacts of precipitation extreme on different urban sub-ecosystem health are diverse or even adverse.

In contrast, economic system is easier to recover than the ecological system after climatic disaster. Government measures for recovering urban ecosystem health may emphasize sub-ecosystems of vigor, organization and emergies, these three are susceptible to the climatic extreme and the subsequent impacts are innegligible. In addition, policy makers should also pay more attention on environmental loading rate, measures like advocating improving energy use efficiency can be adopted for sustainable development and risk mitigation in the context of climate change.

However, our research is still potential to be further improved if we can do field survey to get specific data like urban waterlogging, how much is the loss of urban discharge system? It is also one of the most important parts for urban ecosystem health facing extreme precipitation. Moreover, urban the submergence area is unknown, and this is one of the most significant control variable for DiD method, when we try to obtain the impacts of extreme precipitation on urban ecosystem health.

Conflicts of interest

The authors declare that there is no conflict of interests regarding the publication of this paper.

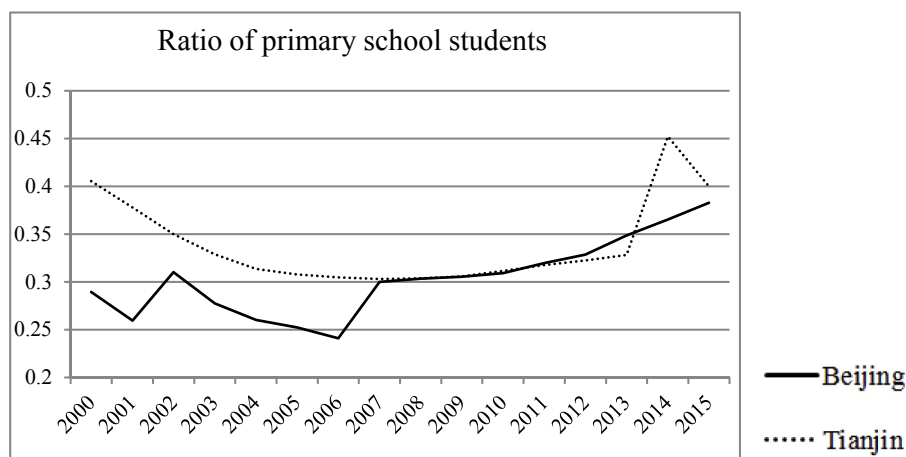


Fig. 5. Ratio of primary school students in Beijing and Tianjin during 2000–2015.

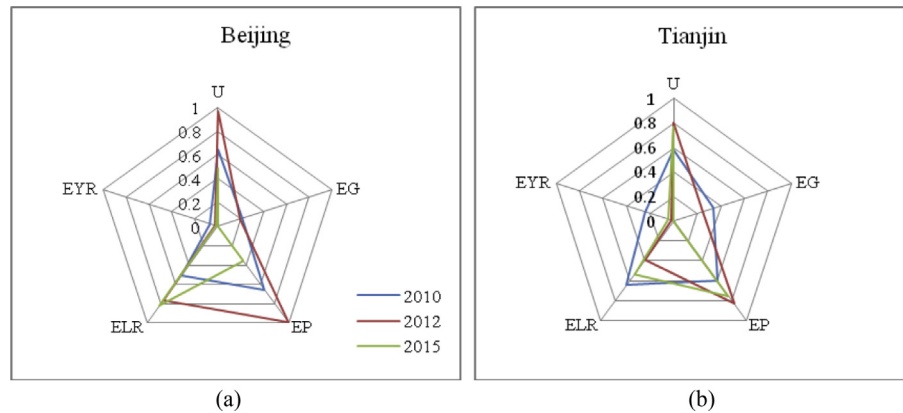


Fig. 6. Radar maps of emergies for Beijing and Tianjin in the year of 2010, 2012 and 2015. **Note:** Here U refers to total energy, EG, EP, ELR and EYR are energy/dollar ratio, per capita energy welfare, environmental loading rate and energy yield ratio separately.

Table 9

Results from Difference-in-Difference approach analyzing the impact of precipitation extreme on urban sub-ecosystem health of emergies.

Beijing vs. Tianjin (D)	Pre-precipitation extreme vs. Post-precipitation extreme (T)	Interaction term (D × T)	Constant
Dependent variable: Total energy in Beijing and Tianjin from 2000 to 2015 25.22(11.57)***	5.76(1.87)	8.32(1.91)**	4.99(3.24)***
Dependent variable: Energy/dollar ratio in Beijing and Tianjin from 2000 to 2015 30.94(7.98)***	−3.74(−0.68)	−16.23(−2.09)**	11.02(4.02)***
Dependent variable: Per capita energy welfare in Beijing and Tianjin from 2000 to 2015 19.98 (12.66)***	5.44 (2.44)*	2.90(0.92)	5.21 (4.67)***
Dependent variable: Environmental loading rate in Beijing and Tianjin from 2000 to 2015 −34.69(−6.14)***	40.24(5.03)***	−37.98(−3.36)***	35.90(8.98)***
Dependent variable: Energy yield ratio in Beijing and Tianjin from 2000 to 2015 1.44(2.91)***	−0.53(−0.75)	−1.59(−1.61)*	2.10(5.99)***

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Appendix. Notion list for our research

Concept	Description
healthy ecosystem	defined as being ‘stable and sustainable’, maintaining its organization and autonomy over time and its resilience to stress (Rapport, 1989).
vigor	is measured the urban ecosystem from the perspective of its activity, metabolism or primary productivity (Rapport, 1989).
organization	the diversity and number of interactions between system components (Rapport, 1989).
resilience	be assessed in terms of a system's capacity to maintain structure and function in the presence of stress (Rapport, 1989).
total energy	total energy without exports and wastes (Liu et al., 2009).
emdollar ratio	the ratio of total energy to GDP (Liu et al., 2009).
per capita energy welfare	the ratio of total energy to population (Liu et al., 2009).
environmental loading rate	the ratio of non-renewable resource energy and imported energy to renewable resource energy (Liu et al., 2009).
energy yield ratio	the ratio of total to imported energy (Liu et al., 2009).

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